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WOOD AND OTHER RENEWABLE RESOURCES

Forestry operations in the alpine context. Life cycle assessment to support the integrated assessment of forest wood short supply chain

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Abstract

Purpose Biotic resources are considered a key element of bio-economy. In the present study we focus on the forest supply industry, assessing environmental sustainability through Life Cycle Assessment (LCA) methodology. We explored and evaluated forestry operations in order to support decision-makers in choosing the best operational modes for site-specific conditions. Main aims of the study are: 1) a LCA-based systematic comparative analysis of different operational modes and technological options associated with wood extraction considering site-specific conditions; 2) the quantification of impacts associated with transport of wood material.

Methods A case study on the alpine region of Italy (Intelvi Valley) is presented and discussed. Different forestry activities were investigated, comparing the traditional operational method with a more mechanized one (advanced mechanization). All operations were included within the system boundaries, from felling to transport to sawmill. Regarding the traditional operational method, different options were evaluated, considering that: 1) the extraction could be performed by cable-yard or winch; and 2) the delimbing phase could be performed before or after extraction phase. Each activity was modeled using primary data, assuring that real forest conditions are taken into account and assessed.

Results In spite of the expectations associated with advanced mechanization, the hypothesis to choose traditional mechanization was preferable for Intelvi Valley conditions. Fuel consumption and related emissions proved to be the main source of impacts. Sensitivity analyses highlighted that advanced mechanization could be the best method to perform forestry operations, if used in proper conditions (i.e. at the top productivity rate) and that the choice of a short supply chain drastically reduces the impacts induced by long distance transportation.

Conclusions The choice of the best technological options should be based on a site-specific and context- related assessment. It is very important to give priority to the operational mode which minimizes the hours necessary to perform each operation. It was also found that the technological option should be chosen according to the geomorphology and topography and the site-specific characteristics of the area investigated, and no one option can be considered as the most suitable for all conditions.Furthermore, current impact assessment methods are still lacking in the evaluation of potential impact to biodiversity in the specific context were the extraction takes place. Further investigations related to the environmental profile of a product will be object of a second study that will concern the design of green furniture pieces, starting from certified wood as raw material.

Keywords Environmental impact assessment · Forest mechanization · Forest operations · LCA · Short supply-chain · Wood

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1 Introduction

Bio-economy has increasingly been considered strategic for the transition towards sustainable and green economies. Amongst the other biotic resources, forest resources play an important role, providing raw materials while also ensuring

various ecosystem services and functions, which have to be protected and maintained.

Concerning the economic profitability, forest-based products and related industries make up one of the most important sectors in the European Union, representing about 10 % of the total manufacturing industries. The forest-wood supply chain is a complex system and groups several different areas of products, such as pulp and paper, paper and board, graphic industry woodworking and furniture (Gonzalez-Garcia et al. 2009a). Hence, a proper evaluation of this industry sector to improve the sustainability of the whole supply chain is paramount. Life Cycle Assessment (LCA) methodology is identified as one of the most reliable methodologies for evidencing and analyzing the environmental impacts and should be part of the decision-making process toward sustainability (Baumann and Tillman 2004).

Several LCA-based studies have been already carried out in relation to forest operations (Aldentun 2002; Berg and Lindholm 2005; Gonzalez-Garcia et al. 2009b,c; Nebel and Nielsen, 2005; Michelsen 2007; Michelsen et al. 2008), highlighting that the greatest environmental burdens are induced by fuel consumption of machineries in most cases. Michelsen et al. (2008) found that extraction operations and transports are responsible for 85 % of the total environmental impacts of a wood-timber supply chain. An exhaustive study regarding wood production in Italy is provided by Cambria and Pierangeli (2012), which examined the production of high quality timber deriving from walnut tree plantations. Werner and Nebel (2007) highlighted that it is difficult to compare logging in certified and non certified forests, because the current LCIA methods can hardly account for differences in the impacts to biodiversity stemming from sustainable or unsustainable forest management.

In the context of an eco-innovation pilot project illustrated in section 2, the aims of the present study were twofold: 1) a LCA-based systematic comparative analysis of different operational modes and technological options associated with wood extraction considering site specific conditions; 2) the quantification of impacts associated with transport of wood material. Furthermore, as claimed by Kranzberg (1986), every technology is neither good nor bad, nor is it neutral, hence this study wants to apply a systemic and scientific evaluation to identify the best solutions available for a specific context and provide an objective environmental impact assessment of the options proposed.

The paper is structured as follows. Section 2 provides a general introduction to the pilot eco-innovation project at local scale and clarifies the background and the aim of the study. The LCA of forestry operations is reported in section 3, specifying LCA methodological aspects, such as: the goal and scope of the study, functions and functional unit and system boundaries. A detailed inventory of data used is described in section 4, followed by a summary of results obtained in the Life Cycle Impact Assessment stages, namely characterization and normalization (section 5). A sensitivity analysis of results and discussion about the influence of transports is provided in section 6, conclusions and future outlook are presented in section 7.

2 Background of the case study

The current study has been developed in the context of a pilot interdisciplinary project on sustainability of wood short-supply chain, as leverage for local development in mountain areas (BOMO project). The aim was to understand the specific context and the added value of undertaking an LCA. The case study was located in Lombardy Region (Northern Italy). Lombardy's forest area is estimated at 620,122 hectares (at 2010), with an increase of 1,079 ha compared to the estimate of the previous year (ERSAF 2011). The timber and furniture industry, with 15 % of all businesses and 9 % of all workers in Italy's manufacturing sector, is the second biggest in Italy (Federlegno 2010). In Lombardy it is possible to distinguish the following sectors: (1) forestry; (2) woodworking; (Baumann and Tillman 2004) energy from biomass. Lombardy has a great potential in terms of wood availability, but forest resources are currently not properly capitalized. Only one-third of the timber used in Lombardy comes from this region, even if there could be enough local wood to satisfy the local needs. The remaining two-thirds mostly come from Eastern Europe, due to its competitive prices and good quality.

Therefore, the BOMO project (*Bosco-Mobile*, Forest-Furniture) was undertaken to study the economic potential and viability of forests located in the region of Lombardy and to explore the benefits which could be provided by a short supply chain scheme.[1] The project encompassed an attempt to create a short supply chain in Lombardy, using the wood coming from Intelvi Valley, located in North-East Lombardy, to produce furniture in the local small and medium enterprises' district (Lissone furniture district in Northern Italy). For this purpose, a pilot supply chain using the certified wood from the forests managed by the Lario Intelvese Forest Consortium (LIFC), within Intelvi Valley, was taken as a reference.

The prevalent land use of the Intelvi Valley is forest and there is a great extent of meadows and pastures. It is not possible to identify a homogenous type of wood species, due to the high variability of conditions in the valley; the most important are chestnuts, oaks, maples, ashes and beeches (Radrizzani and Beccarelli 2006). Forest operations are usually conducted by small or individual enterprises with low mechanized equipment (saw chains and winch or cable logging). The introduction of more advanced mechanization systems in this area seems promising to local experts, due to

[1] A short supply chain scheme is defined by short distances (within 70 km) and a small number of intermediaries

the nominal higher productivity of harvester and forwarders, which could improve also environmental performance of forestry operations. For this reason, field trials have been done during the last years. Nevertheless, no information is available about potential environmental impacts arising from the application in this specific context. Therefore, detailed evaluation through LCA is needed to support informed decision making about the most suitable technology to be chosen.

3 Life cycle assessment of forestry operations

3.1 Goal and scope of the LCA

Life Cycle Assessment (LCA) methodology was chosen to perform a comparative analysis of different operational modes and technological options for wood extraction from forest in order to identify the best mechanization method for the site under investigation (relative small areas with deep slope).

Intelvi Valley was taken as case study for assessing different scenarios. Firstly, two different possibilities of extraction (by winch and cable-logging) were assessed; secondly, the introduction of a new advanced mechanization (with harvester and forwarder) were tested to highlight, if any, the environmental benefits in comparison to business as usual (i.e. traditional mechanization systems usually applied in Intelvi valley). A third comparison regarded the operation of delimbing before or after the extraction in the traditional mechanization mode.

Furthermore, to test the environmental effects produced by transports, a comparison between BOMO timber and timber generally used in the Lissone furniture district ("standard timber" hereinafter) was performed. As discussed with local experts, the Lissone district usually buy timber from Central Europe or from Ukraine, due to the technological characteristics (more regular logs) and the price thereof. Therefore timber coming from Eastern Europe was taken as a reference for the comparison with the timber coming from the Intelvi valley short supply chain.

3.2 Function and functional unit

The function of the system under study is the extraction of timber and its transport to sawmill. The functional unit is defined as *1 ton of timber* and it represents the reference point for inputs and outputs of the system under study (ISO 14040, 2006). Data used in this study came from field studies and were collected with the support of the project partners. Three different species of trees were extracted from Intelvi Valley forests, maple, beech and ash; hence it was necessary to refer all data and calculations to them. All input data about timber referred to the volume (m^3) of extracted wood, hence it was necessary to transform these data to correspond with our functional unit. First, the volumic mass was calculated according to 1

$$\rho_w = \rho_0 * \left[1 + \left(u/100\right)\right] \Big/ \left[1 + \left(a_v/100\right)\right] \tag{1}$$

where: (1) ρ_w stands for volumic mass with moisture content u [kg/m^3]; (2) ρ_0 stands for volumic mass referred to anhydrous status [kg/m^3]; (Baumann and Tillman 2004) u stands for moisture content of the wood [%]; and a_v stands for total volumetric swelling factor [%]. ρ_0 and a_v values vary according to the wood species (AIEL 2009). Since a_v values are not available for ash, beech, and maple, these were calculated using β_v, total volumetric shrinkage factor [%], whose values are reported in Table 1. Moisture content is assumed to be 80 % (AIEL, 2009). Table 1 shows the values of the different terms calculated for the three species.

$$a_v = (100 * \beta_v) \Big/ (100 - \beta_v) \tag{2}$$

The average volumic mass for the three species is 1000 kg/m^3. Regarding the calculation of dendrometric and thermometric volume, beech trees were taken as reference, due to a major availability and consistency of data regarding these species. The average diameter for the trees in this area is 30 cm, measured at 130 cm height from the ground. According to stereometric and allometric tables by Hellrigl (2006), the dendrometric volume (that is the sum of trunk, bark, tops and branches) is about 0.795 m^3 (equivalent to 0.795 tons), while thermometric volume (trunk and bark) is about 0.572 m^3 (equivalent to 0.572 tons), that means a volume reduction of about 28 %. It follows that, 1.39 tons of fallen wood is needed to obtain 1 ton of usable timber.

3.3 System boundaries

In order to assess the environmental impacts of the short supply chain scheme, this was split up into two macro-systems, according to the aims of the project: 1) evaluation and comparison of different procedures for forestry operations (traditional mechanization versus advanced mechanization); 2) woodworking (from wood panels manufacturing to finished furniture). The decision to distinguish these two

Table 1 Volumic mass, total volumetric shrinkage and swelling factors for ash, beech and maple

Species	ρ_w [kg/m^3]	ρ_0 [kg/m^3]	a_v [%]	β_v [%]
Maple	912.4	590.0	13.0	11.5
Ash	1036.1	670.0	15.2	13.2
Beech	1051.5	680.0	21.0	17.3
Average	1000.0	646.7	16.4	14.0

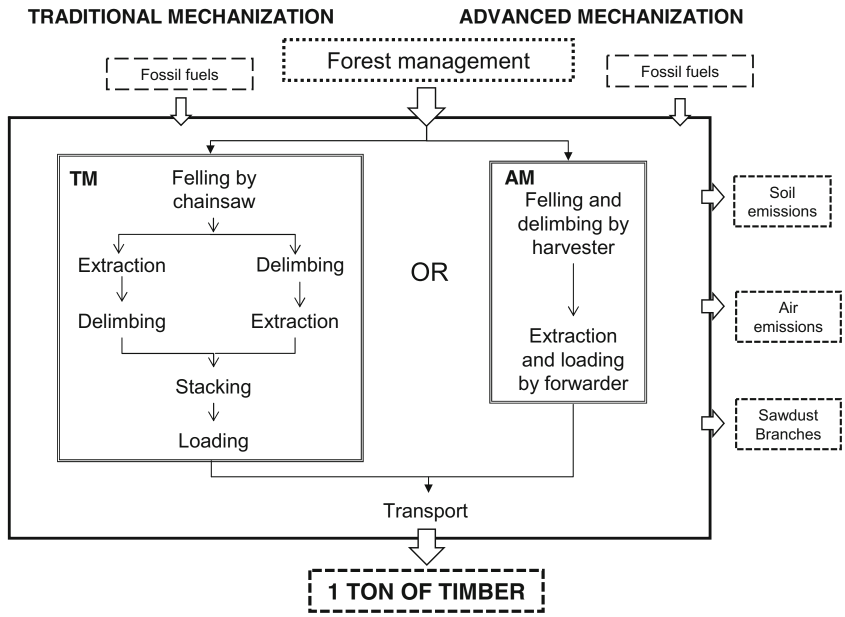

Fig. 1 System boundaries under study for traditional and advanced mechanization.TM stands for traditional mechanization, AM for advanced mechanization

macro-phases came from the following considerations: (1) lack of reliable data regarding sawmilling operations; (2) no influences of drying operation, since this was conducted with natural air. Hence, these two phases were excluded from the evaluation. The present paper refers to the the analysis of the forest mechanization options. A subsequent study to complete the analysis of the supply chain is reported in (Mirabella et al. 2014).

The system under study included forestry activities (cutting, delimbing and extraction) performed with different levels of mechanization. Figure 1 summarizes the organization of forest sites and the phases analyzed in this study. Traditional mechanization (first option) included six different phases: (1) felling; (2) extraction (by winch or cable-logging); (3) delimbing; (4) stacking; (5) loading; (6) transport to sawmill. Advanced mechanization (second option) considered the use of heavy vehicles, such as harvester and forwarder; this kind of mechanization allows the combination of multiple operations, reducing the number of processes considered. Therefore, only three phases were identified: (1) felling and delimbing; (2) extraction; (3) transport to sawmill. Figure 2 focuses on the different options investigated for traditional mechanization, dividing the traditional mechanization method into four different options. The four options that follow a traditional mechanization scheme were: (1) extraction performed by cable-yard before delimbing phase (cable-logging pre-delimbing); (2) extraction performed by cable-yard after delimbing phase (cable-logging post-delimbing); (3) extraction performed by winch before delimbing phase (winch pre-delimbing); (4) extraction performed by winch after delimbing phase (winch post-delimbing).

Machine use was taken into account calculating the fossil fuels needed to perform each operation and the emissions produced, while machine production was excluded. The

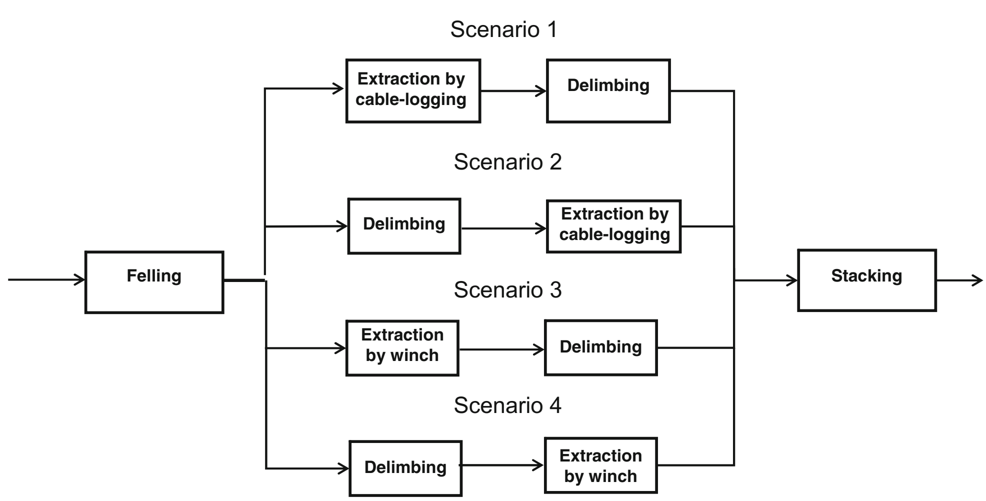

Fig. 2 Focus of 4 different scenarios for extraction and delimbing in traditional mechanization

production of capital goods (machineries, buildings and roads) and transport of energy carriers were not included within system boundaries, since the contribution of their manufacturing was found to be negligible (long life time and high number of operations performed) compared to their operation stage (Jungmeier et al. 2002; Rivela et al. 2006). The transport of workers and the maintenance were not included in the system boundaries. The workforce is supposed to be local, with negligible transport related impacts.

Hence the options compared within this study were four regarding traditional mechanization and one regarding advanced mechanization.

4 Life cycle inventory

Life cycle inventory phase involves the compilation and quantification of inputs and outputs of the system considered (ISO 14040, 2006). The inventory and data collected for traditional and advanced mechanization, plus a final discussion about data quality and inventory results, are detailed in this section. Each work phase of traditional and advanced mechanization was modeled evaluating the time necessary to obtain 1 ton of timber (in hours) and, for each step, hourly fuel consumption and emissions were examined. Time studies were performed for mechanized operations (details can be found in Spinelli et al. 2009, in Italian), whereas for traditional operations data about time and related consumption were provided by local experts, based on the same time studies and on empirical experience about the different options considered (e.g. delimbing before or after the harvesting). It was not possible to use only the data from time studies performed on the same stands because some of the options explored were not included in the tests. In those cases, average data about fuel consumption for the operations made in the same area and in the same conditions were used (provided by the local experts from the LIFC). The method applied in both cases is classified as "shift level" in the classification proposed by Magagnotti and Spinelli (2012) and consists of recording the total time for team work, major delays for each worker and the total amount of timber produced in each half day of work.

4.1 Traditional mechanization

The different options presented in Fig. 2 were evaluated and compared in order to identify which have the lowest potential environmental impacts and to support the LIFC in its operational choices. Since forestry operations were not available on Ecoinvent database, every step was modeled using primary data and information provided by LIFC. Uncertainties and statistical analysis could not be estimated, since the sample of data available was insufficient. Data provided for each phase were: (1) machinery used (number and type of equipment); (2) fuels and oil average daily consumption; (3) average daily productivity of timber. All the details of the inventory for each step (felling, extraction, delimbing, stacking, loading and transport), with the values adopted are reported in supporting information (SI).

4.2 Advanced mechanization

This scenario implied the use of more modern and technological means, with harvester and forwarder, provided by a firm located in Trentino Alto-Adige region (Northern Italy). The introduction of these machines and new modalities to perform these forestry operations was considered as a future option by LIFC. The aim was to find a more suitable method both from the environmental, and productivity point of view and to compare the two operations options (traditional mechanization and advanced). Since forestry operations were not available on Ecoinvent database, every step was modeled according to primary data provided by LIFC (Spinelli et al. 2009). The modalities of interventions described in this paper refer to the operations performed by a forestry firm operative in Trentino Alto-Adige region, that has at its disposal more modern means (year of purchase 2005). It is important to remark that the geomorphology and the topography of the Intelvi Valley, as presented in section 1.1, inhibits the harvester and forwarder from reaching maximum productivity, that is about 40 m^3/h of timber. This issue and further considerations were accounted for in the sensitivity analysis. All the details of the inventory for each step (felling and delimbing, extraction and loading, and transport), with the values adopted are reported in the Electronic Supplementary Material (ESM).

4.3 Data quality and inventory results

According to the ISO 14040 series (2006), the LCI can be compiled from primary, secondary and estimated data. In this study a mix of primary and secondary data were used. Primary data were obtained by on-site measurements and were collected through interviews, informal conversations and visits to local forestry sites. They regarded on-site measurements of forestry operation phases in Intelvi Valley area. These data referred to the amount of wood extracted, as well as machineries used and their fuel consumptions. In LCA studies, the use of specific and local data is of great importance whenever possible (ISO 14040, 2006; Ossés de Eicker et al. 2010). Other inventory data about operations themselves were obtained from Ecoinvent database, incorporated in SimaPro version 7.2. These are mainly fuel consumption of machinery (diesel or gasoline) and related emissions for each forestry activity. Inventory data for emissions in the use phase of machineries were drawn from "Non road emission database" by Swiss FOEN (Federal Office for the Environment 2010).

This report quantifies non-road pollutant emissions and fuel consumption in Switzerland. This source encompasses all mobile machines and appliances that are equipped with a combustion engine and are not intended to transport passengers and goods by road. The choice of a Swiss database was justified by the absence of databases that collect national data. Furthermore the choice was consistent from the geographical point of view, due to the proximity of the areas. The database provided specific data on hours of operation (hours per machine, according to year of production) and the emission factors (kg/hour) of non-road machineries and appliances. In particular, the database contained data for vehicles with or without a particulate filter, hydrocarbon (HC), carbon monoxide (CO), nitrous oxides (NO_x), particulate matter (PM), fuel consumption (FC) and carbon dioxide (CO_2). For every kind of machinery it distinguished the results according to the power. For our case study, we referred to forestry machinery, choosing machine type (chainsaw, cable-crane, etc.), engine type (diesel or gasoline) and capacity (low 18–37 kW, medium 37–75 kW and high 75–130 kW), according to the equipment used in Intelvi Valley to perform the described operations. Since almost all of the equipment on-site used in traditional mechanization was relatively old, the year of construction 2000 was used as reference point. Harvesters and forwarders were supposedly newer, thus it was decided to use 2005 data. Inventory data regarding the different operational modes and phases (with time of work, fuel consumption and emissions factors) are summarized in Table 2 (traditional mechanization) and Table 3 (advanced mechanization).

5 Life cycle impact assessment and results

The life cycle impact assessment has been conducted entailing classification, characterization and normalization stages (ISO 14040 2006). Recipe 2008, was chosen as Life Cycle Impact Assessment method, for its completeness (Goedkoop et al. 2009). The impact categories considered in this study were: climate change (GWP), ozone depletion (OD), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial acidification (TA), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FE), marine ecotoxicity (ME) and fossil depletion (FD). Other categories (namely agriculture land and urban land occupation, natural land transformation, water and mineral resources depletion, ionizing radiation) showed output values equal to zero, therefore they were excluded. Concerns about ground (soil) damages due to mechanization and tyre pressure could be significant for forestry ecosystem, especially because soil compaction can cause higher runoff and alterate hydrogeological cycles, but they are out of scope of this study and were not evaluated.

Table 2 Traditional mechanization inventory data for the four different operational modes

	Input to the system							Output to the system				
	Time of work [hr/ton]				Fuel consumption [kg/hr]			Emissions [kg/hr]				
Forestry activity	*Cable logging, pre-delimbing*	*Cable logging, post-delimbing*	*Winch, pre-delimbing*	*Winch, post-delimbing*	*Diesel*	*Oil*	*Lubricating oil*	*HC*	*CO*	*NOx*	*CO_2*	*PM*
Felling	0.107	0.107	0.107	0.107	-	2.35	1.35	0.911	2.086	0.006	7.126	-
Extraction	0.035	0.009	0.059	0.019	4.95[1] 5.36[2]	-	-	0.021[1] 0.018[2]	0.1217[1] 0.0922[2]	0.2169[1] 0.1295[2]	17.351[1] 11.171[2]	0.013[1] 0.014[2]
Delimbing	0.083	0.083	0.083	0.083	-	2.35	1.35	0.911	20.864	0.0063	71.262	-
Stacking	0.078	0.078	0.078	0.078	13.2	-	-	0.050	0.2880	0.5185	32.033	0.031
Loading	0.019	0.019	0.019	0.019	6.6	-	-	0.028	0.1137	0.1606	12.734	0.017
Transport	0.098	0.098	0.098	0.098	6.6	-	-	0.028	0.1137	0.1606	12.734	0.017
Total	0.42	0.394	0.444	0.4038	31.35[a] 31.76[b]	4.70	2.70	1.038[1] 1.035[2]	23.59[1] 23.56[2]	1.069[1] 0.981[2]	153.24[1] 147[2]	0,078[1] 0,079[2]

[a] Cable-logging

[b] Winch

Table 3 Advanced mechanization inventory data

Forestry activity	Input to the system		Output to the system				
	Time of work	Fuel consumption	Emissions [kg/hr]				
	[hr/ton]	*Diesel [kg/hr]*	*HC*	*CO*	*NOx*	*CO_2*	*PM*
Felling and delimbing	0.072	10.2	0.0545	0.3157	0.6353	50.7378	0.0346
Extraction and loading	0.071	9.35	0.0410	0.2195	0.3950	32.0325	0.0262
Transport	0.098	9.35	0.0410	0.2195	0.3950	32.0325	0.0262
Total	0.24	28.90	0.14	0.75	1.43	114.803	262.06

5.1 Results of the five options evaluation - characterization stage

The comparison of results of the five operation modalities for the characterization step is shown in Fig. 3. The options implying the greatest environmental burdens were: (1) traditional mechanization by winch extraction before delimbing and 2) advanced mechanization. Option (2) presented the highest contributions to the following categories: ozone depletion, human toxicity, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and fossil depletion. Option (2) had a major burden to the following categories: climate change, photochemical oxidant formation, particulate matter formation, terrestrial acidification and marine eutrophication. At the same time, option (2) was the most favorable choice for the other categories. The activities that mostly affected the overall impacts were: (1) the consumption of fossil fuels for the machinery use (Castellani et al. 2010), confirmed also by previous studies in the same field (Berg and Lindholm 2005; Michelsen et al. 2008; Neupane et al. 2011); (2) use of harvester and related diesel requirements and emissions for advanced mechanization; (3) stacking phase for traditional mechanization and related fuel consumption and emissions. Advanced mechanization shows greater impacts for TA, MEP and PMF impact categories, caused by local emissions; this suggests to increase spatial resolution both at the inventory and at life cycle impact assessment phase. In order to identify the most important sources of impact, a more detailed study of each impact category was carried out.

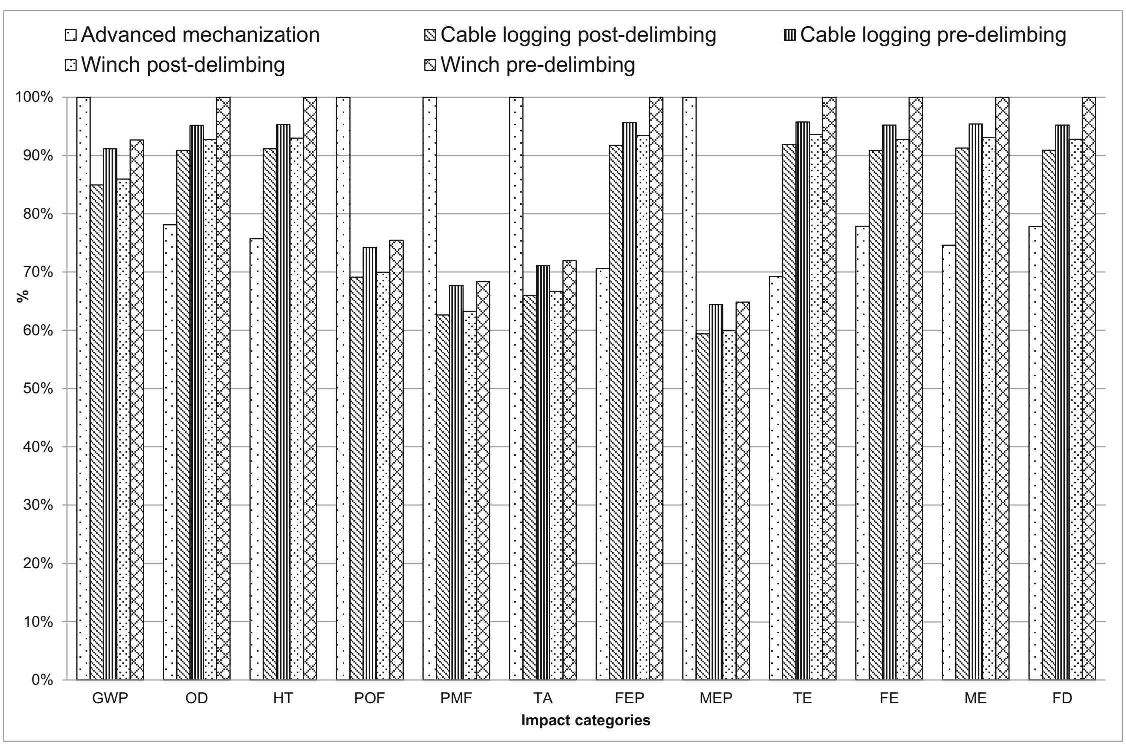

Fig. 3 Results for characterization phase, comparison of the five operation modalities (in %)

5.1.1 Climate change

Advanced mechanization was the operational option with the greatest contributions to this impact category, mainly due to CO_2 (97 %) and CH_4 (about 3 %) airborne emissions related to the use of the harvester (responsible for 44 % of the overall emissions). The use of the forwarder contributed for 27 %, transports for 14 %.

5.1.2 Ozone depletion

As presented in Fig. 3, the use of the winch before delimbing option was the main contributor to ozone depletion, mainly due to diesel requirement (for about 71 %) and petrol (20 %). Airborne emissions of halon 1301 accounted for almost 100 % of the total.

5.1.3 Human toxicity

Just as for the previous impact category, the use of the winch before delimbing was again the main source of impacts, always related to its diesel consumption (69 %) and petrol (23 %). Regarding the main substances contributing, barium (about 85 %), mercury (4 %), lead (2.7 %) and cadmium (2.6 %) represented the majority of the released emissions.

5.1.4 Photochemical oxidant formation, particulate matter formation and terrestrial acidification

For these categories, major potential environmental impacts were associated with advanced mechanization, due to the use of the harvester (33 % POF, 37 % PMF and 35 % TA) and forwarder (28 % POF, 30 % TA, PMF 31 %). Substances contributing were nitrous oxides (86 % for POF, 91 % for TA, 95 % for PMF), non-methane volatile organic compounds (14 % for POF) and sulfur oxides (9 % for TA and 4.7 % for PMF).

5.1.5 Freshwater eutrophication

The use of the winch before delimbing was the least favorable option for this impact category. This result was again attributed to the high diesel (64 %) and petrol (29 %) consumption. Waterborne phosphate emissions represented the only type of pollutant released for this phase.

5.1.6 Marine eutrophication

Major potential environmental impacts on marine eutrophication were associated with advanced mechanization, due to the use of the harvester, with a contribution of 38.9 %, transports (32 %) and forwarder (23 %). Substances contributing to the impact were nitrous oxides and total nitrogen (99 % and 0.5 %, respectively).

5.1.7 Terrestrial ecotoxicity, marine ecotoxicity, freshwater ecotoxicity, fossil depletion

The use of the winch before delimbing seemed the worst option for the remaining four categories. The main emissions contributing were nickel and zinc releases (69 % and 23 %, respectively) for TE, aromatic hydrocarbons and barium (55 % and 40 % respectively) for ME, barium and nickel (62 % and 29 %) for FE. For FD, the use of oil and natural gas (95 % and 4 %, respectively) were the major contributors. The main cause for all the impact categories was related to diesel consumption.

5.2 Normalization stage

Due to controversial results found regarding advanced mechanization, it was decided to perform a normalization step, in order to assess which phases have the highest relative contributions to overall impacts. Figure 4 shows the ReCiPe 2008 midpoint category results per functional unit, normalized to the emission due to an average European citizen in one year. Normalized results show that for photochemical oxidant formation, particulate matter formation, terrestrial acidification and marine eutrophication the incidence of advanced mechanization was particularly significant. Therefore the hypothesis to choose traditional mechanization (cable-logging post delimbing) seemed the preferable way for Intelvi Valley conditions.

6 Discussion of the results for the five options

LCA allowed for the comparison of different kinds of forestry operations, identifying which was the most suitable method to be used for the area investigated. In this case study, five different options were considered and compared, collecting primary data for the area and modeling the operations conditions in detail. This allowed for the identification of the environmental burdens and hot-spots related to operation in the specific forestry area under assessment. The best operation at local scale was the traditional mechanization with the use of cable-logging post-delimbing. Indeed, according to Figs. 3 and 4, two processes were significantly critical for the system under study: advanced mechanization and traditional mechanization with extraction operations performed by winch pre-delimbing. In fact, extraction before delimbing did not allow the machines (both cable and winch yarder) to operate at their full potential capacities, since the pulling force was not completely exploited. This extended the time necessary to

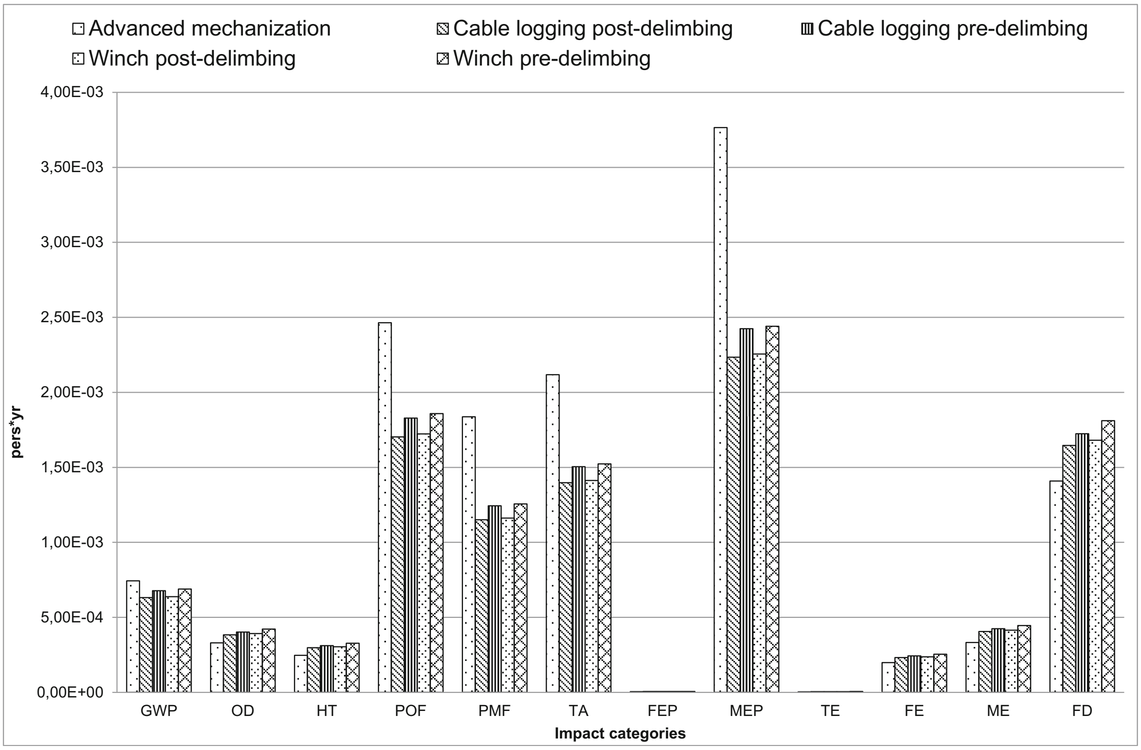

Fig. 4 Results for normalization phase, comparison of the five operation modalities (in %)

perform the operations; therefore, a major amount of fuel was used. Furthermore, the winch was the slowest machine to be employed, and this option was the least favorable to choose. Concerning advanced mechanization, the high fuel consumption and related emissions are usually offset by its high productive capacity, which makes this operational mode a favorable way to perform forestry operations. However, the geomorphology and topography of the area did not allow for the proper exploitation of the machines and lengthened the time required. The emissions of pollutants were consequently increased and make advanced mechanization unsuitable in these conditions. Finally, traditional mechanization appeared as the solution with the lowest environmental impacts. Advanced mechanization could become the preferable option to be adopted in case of an appropriate control of engine emissions and if stricter regulations came into force.

Additionally, the relevance of improving spatial differentiation in the evaluation of the impacts has been highlighted by the results. The impact associated to advanced mechanization (photochemical oxidant formation; particulate matter formation: and terrestrial acidification) might be evaluated considering site-specific aspects, due to contribution to local impacts.

6.1 Sensitivity analysis

A sensitivity analysis of the results related to the five options was performed taking into account: 1) the implementation of an option in which harvesters and forwarder were used at their highest productivity (about 40 m^3/h of timber extracted) and comparing the results obtained with traditional mechanization; 2) the adoption of Best Available Technologies (BAT) in terms of emissions reduction attributed to engines. The functional unit is always 1 ton of timber.

Results of the first sensitivity analysis showed that in these conditions, advanced mechanization represented the preferable option from the environmental point of view, due to the higher efficiency of machinery in fuel use (see Fig. S1, Electronic Supplementary Material).

If exploiting the maximum productivity of harvesters and forwarders is not possible (as in the Intelvi Valley case), the choice of machines equipped with diesel particulate filters (DPF) or selective catalytic reduction (SCR) systems can be a viable option to reduce particulate matter and nitrous oxides emissions. Hence, a second sensitivity analysis was performed assuming Intelvi Valley data and conditions and the use of machines furnished with SCR and DPF technology. Based on European laws (Directives 2000/25/CE and 2004/26/CE), a precautionary efficiency removal of 95 % for DPF and 90 % SCR was assumed. Comparison results of the three different scenarios involving advanced mechanization (baseline, top productivity and SCR-DPF scenario) are shown in Fig. S2 (Electronic Supplementary Material).

Figure S2 (ESM) highlights the positive benefits induced adopting DPF and SCR technology. For POF, PMF, TA and MEP reductions for DPF and SCR systems compared to

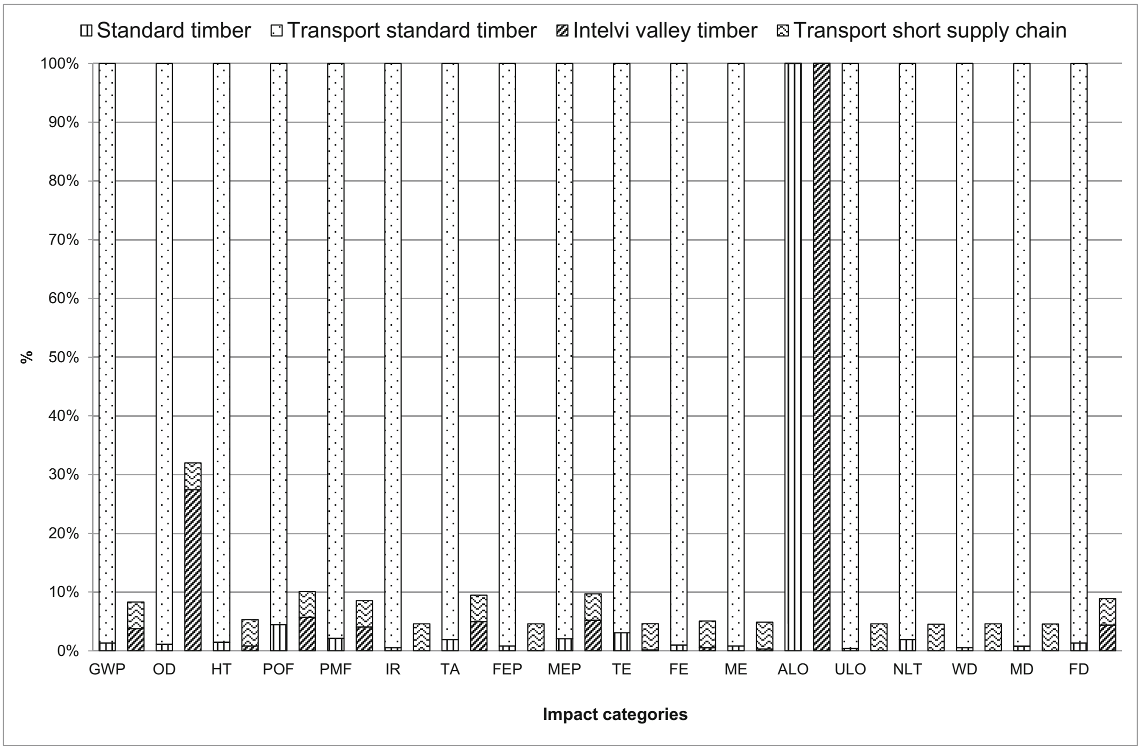

Fig. 5 Comparison of results for standard timber and Intelvi Valley timber, characterization phase (in %)

baseline ranged from 48 % to 55 %. This meant that advanced mechanization equipped with DPF and SCR technologies would solve criticisms raised in previous results. In any case, the use of forwarders and harvesters at top productivity always seemed the preferable option.

6.2 Influence of transport: a comparison between Intelvi Valley timber and Eastern Europe Timber

A further analysis was performed to highlight the environmental burdens incurred by long-distance transports in the case of foreign timber imports. Two different kinds of timber were compared: timber from Intelvi Valley and standard timber coming from Eastern Europe (ERSAF 2011), also suggested by experts as the major exporter in Europe of timber. Average distances along the whole supply chain (from forestry to furniture manufacturers) were considered in the evaluation and were equal to 100 km for Intelvi Valley timber (from Intelvi valley forests to Lissone furniture district) and 1550 km for standard timber. Regarding the standard process to which the local supply chain had been compared, the process “Industrial wood, hardwood, under bark, u=80 %, at forest road” was used from the Eco-invent database, since it was the most suitable to our scope. It comprises all the phases considered for the local supply chain and refers to an average timber supply chain in Central Europe. Use of a lorry of load >32 t was assumed for transports, either from Eastern Europe, and Intelvi Valley. Figure 5 gives the results comparing 1 ton of standard timber and 1 ton of Intelvi Valley timber. New impact categories compared to previous cases were evaluated: ionizing radiation (IR), agriculture and urban land occupation (ALO e ULO), natural land transformation (NLT), water and metal depletion (WD and MD). Intelvi Valley timber gave better results, showing that the use of timber coming from the local supply chain decreased the environmental burden with respect to standard timber from foreign regions. There were improvements in each impact category. The lowest reduction occurred in relation to Ozone depletion (55 %), while in other categories there was a reduction of environmental impacts ranging from 85 % to 99 %. The highest impacts for standard timber were caused transport, as a result of the long distances covered for its supply. Indeed, transports were responsible for significant contributions: at least 80 % for every impact category, except for urban land occupation and natural land transformation. Comparing only the forestry activities for the two types of timber, transport not included, there was no predominance for one of the two methods.

7 Conclusions and outlook

This study focused on the evaluation of two different methods and 5 related options to perform forestry operations in Intelvi Valley (Lombardy region, Northern Italy) associated with traditional mechanization and advanced mechanization. For

the traditional one, several options and machineries were also taken into account. Hot-spots and environmental burdens were identified and assessed from the inventory analysis and impact assessment results. Fuel consumption and related emissions proved to be main source of impacts, hence it was very important to prioritize the operational mode able to minimize the hours necessary to perform every operation. It was also found that each technology should be chosen according to the geomorphology and topography and characteristics of the area investigated, and no one method can be assumed as the most suitable for all conditions. For instance, steep terrains and stands where selective cutting is applied and a limited amount of biomass is harvested can limit the productivity of harvesters and forwarders. Therefore, traditional mechanization with cable-logging post-delimbing seemed to be the best option for the Intelvi Valley case, but through sensitivity analyses it was shown that advanced mechanization at top productivity or equipped with SCR and DPF could be the best solution in other cases. The reason stands in advanced mechanization high productivity that allows several operations to be performed in short time. Finally, the comparison between Intelvi Valley timber and standard timber coming from Eastern Europe stressed the influence of transports, responsible for the greatest environmental burdens.

It is remarkable to remember that it is not yet possible to account for the benefits induced using the wood produced according to certification schemes (such as PEFC or FSC) through the LCA methodology. Indeed, forest certification is a single-issue label and it only certifies the quality of forest management. Forest certification seems to have limited but positive direct impact on sustainable forest management and biodiversity (Rametsteiner and Simula 2003); however, forest is a very complex system itself and can be difficult to quantify as a component of an LCA (Straka and Layton 2010). Concerns about ground (soil) damages due to mechanization and tyre pressure could be significant for forestry ecosystem, especially because soil compaction can cause higher runoff and alterate hydrogeological cycles, but they are out of scope of this study and were not evaluated.

Some final considerations are related to weak points in LCA and LCIA and worth in-depth examination. The results of this case study is strongly local-dependent, but local impacts and benefits are not accounted in LCA, since many LCIA methods and associated models are not site specific. For this reason, possible further benefits or local impacts could not be taken into account. Biotic depletion is not considered by several impact assessment methods, however, it is clear that overexploitation can be source of serious impacts. Further studies could address a sensitivity analysis to the evaluation of biotic depletion potential using different several impact assessment methods. Dealing with biotic resource like wood, a comprehensive environmental sustainability assessment of forest supply chain should be better modeled regarding the land use associated with forest exploitation and biotic resource use, e.g. assessing the carrying capacity of the system (usually not accounted for in impact assessment methods). Nevertheless, a deep analysis of these aspects is beyond the scope of this paper. Acknowledging for the limits of the present evaluation, future research outlooks should be addressed towards a comprehensive sustainability assessment, including the following aspects: 1) capability of LCA to thoroughly address potential benefits induced by using wood produced according to certification schemes (such as PEFC or FSC); 2) conditions under which the technology assessment may be influenced by the local context; 3) possible integration of the environmental sustainability assessment with other dimensions e.g. the local supply chain and social and economic fallout on local employment and economy; 4) integration of comparative analysis with the same approach of LCA but also with a more ecologically oriented assessment, e.g. local impact to terrestrial and soil biodiversity due to the different operation systems.

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